

Ground-Based Gamma-Ray Astronomy

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Abstract. Ground-based γ -ray astronomy has become an active astrophysical discipline with four confirmed sources of TeV γ -rays, two plerionic supernova remnants (SNRs) and two BL Lac objects (BL Lacs). An additional nine objects (one plerion, three shell-type SNRs, one X-ray binary, and four BL Lacs) have been detected but have not been confirmed by independent detections. None of the galactic sources require the presence of hadronic cosmic rays, so definitive evidence of their origin remains elusive. Mrk 421 and Mrk 501 are weak EGRET sources but they exhibit extremely variable TeV emission with spectra that extend beyond 10 TeV. They also exhibit correlations with lower energy photons during multi-wavelength campaigns, providing tests of emission models. Next generation telescopes like VERITAS hold the promise of moving this field dramatically forward.

INTRODUCTION

Since the launch of the *Compton Gamma-Ray Observatory* (CGRO), ground-based γ -ray telescopes have come to play an important role in our understanding of the γ -ray sky. In many cases, it has required the results from both the ground and space to properly interpret the observations of a particular source. In this context, I review the status of ground-based γ -ray astronomy and consider the implications of these observations. I will concentrate on the results obtained with imaging atmospheric Cherenkov telescopes because they have produced most of the scientific results to date and because several papers in this proceedings address other ground-based telescope results. The interested reader is encouraged to seek out more complete reviews that have recently been published [1,2] for more information. To save space, I will not cite the original detection references for those objects that are included in the review articles.

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TABLE 1. Galactic Sources of VHE γ -rays.

Source	Energy	Flux	Significance
Crab Nebula	>0.3 TeV	$1.26 \times 10^{-10} \text{cm}^{-2} \text{s}^{-1}$	Conf. ^a
PSR 1706-44	>1.0 TeV	0.38 Crab	Conf.
Vela	>2.5 TeV	0.54 Crab	5.8σ
SN 1006	>1.7 TeV	0.48 Crab	8.0σ
RXJ 1713.7-3946	>2.0 TeV	0.40 Crab	5.0σ
Cassiopeia A	>0.5 TeV	???	4.7σ
Centaurus X-3	>0.4 TeV	0.24 Crab	6.5σ

^a Significances are listed only for unconfirmed sources.

GALACTIC SOURCES

Seven sources of very high energy (VHE, $E > 250$ GeV) γ -ray emission associated with galactic objects have been detected at this time: three plerionic supernova remnants (SNRs) (Crab Nebula, PSR 1706-44, and Vela), three shell-type SNRs (SN 1006, RXJ 1713.7-3946 [3], and Cassiopeia A [4]), and the X-ray binary Centaurus X-3 [5]. A summary of the VHE properties of these objects is given in Table 1. The Crab Nebula and PSR 1706-44 have been confirmed as sources of VHE γ -rays by detections from independent groups. The Crab Nebula has the highest VHE γ -ray flux of these objects and this, along with its steady flux, has established it as the standard candle of ground-based γ -ray astronomy. Because of this and because ground-based γ -ray telescopes have a range of energy thresholds, I list source fluxes in units of the Crab flux to make comparisons of source strength easier.

All three of the detected plerions are EGRET sources [6], but the GeV emission is predominantly or entirely pulsed, while the TeV emission shows no evidence of pulsations. This is consistent with the VHE emission arising in the synchrotron nebulae of these objects. Several groups have measured accurately the spectrum of the Crab Nebula over an energy range spanning 250 GeV to 50 TeV. The spectrum is fit well by a simple power law with differential spectral index 2.5. The sub-GeV flux measurements, combined with the VHE measurements, are consistent with synchrotron self-Compton emission models for a magnetic field of $\sim 160 \mu\text{G}$ [7]. An interesting feature of the TeV emission detected from Vela is that the peak in the TeV emission is located $\sim 0.14^\circ$ away from the pulsar position, coincident with the birthplace of the pulsar. An upper limit of 0.40 Crab above 300 GeV for Vela [8] implies that its spectrum must be harder than $E^{-2.3}$.

In addition to the plerions listed above, the pulsars detected by EGRET have been searched for VHE emission. None have been detected, and the pulsed flux from these objects must have a rapid decrease in power output between ~ 1 GeV and 300 GeV. Evidence for such cut-offs is seen in the EGRET data for some of these objects [9], but for PSR 1951+32, the power output increases up to at least 10 GeV. The Whipple collaboration's upper limit on this object is ~ 0.02 Crab [10], implying an extremely rapid fall off in the flux. Similarly, recent upper limits derived for

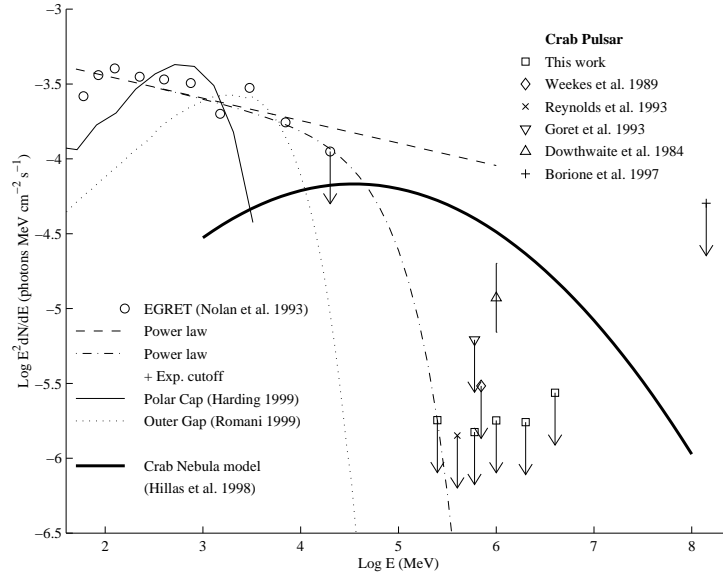


FIGURE 1. The pulsed γ -ray spectrum of the Crab Nebula. The open circles are EGRET flux points and the points with arrows are upper limits. The thick solid line is a model of the unpulsed inverse Compton spectrum. The thin solid and dotted lines are model fits and the dot-dashed line is an extension of the EGRET spectrum with a 60 GeV exponential cut-off. Figure from [11].

pulsed emission from the Crab Nebula imply that if the cut-off is exponential, it must begin below 60 GeV, though this does not constrain the emission models (see Figure 1) [11].

Shell-type SNRs are believed to be sources of γ -rays produced by cosmic rays accelerated in the supernova shocks. In support of this, several EGRET sources are associated with shell-type SNRs [12]. However, the EGRET detections alone are not enough to claim definitively that the long-sought origins of cosmic rays have been found. Indeed, observations by the Whipple collaboration of several of the shell-type SNRs associated with the EGRET sources revealed no evidence of VHE γ -ray emission [13]. The limits derived from those observations imply that if the emission seen by EGRET is from the SNR shells and is produced by the interactions of cosmic rays, then the source cosmic-ray spectrum must be steeper than the $E^{-2.3}$ or that the spectrum cuts off below 10 TeV.

The three detected shell-type SNRs also do not require the presence of hadronic cosmic rays to produce the γ -rays. In all three objects, X-ray synchrotron emission has been detected, implying the presence of > 10 TeV electrons. Thus, the TeV detections can be explained as inverse Compton emission. This is supported by the EGRET's non-detection of these objects and by the positional coincidence of the TeV and X-ray synchrotron emission peaks in SN1006 and RXJ 1713.7-3946 (see Figure 2, [3,14]). If the TeV emission from SN1006 is produced from inverse Compton emission, the magnetic field in the shock region must be $6.5 \pm 2 \mu\text{G}$ [14].

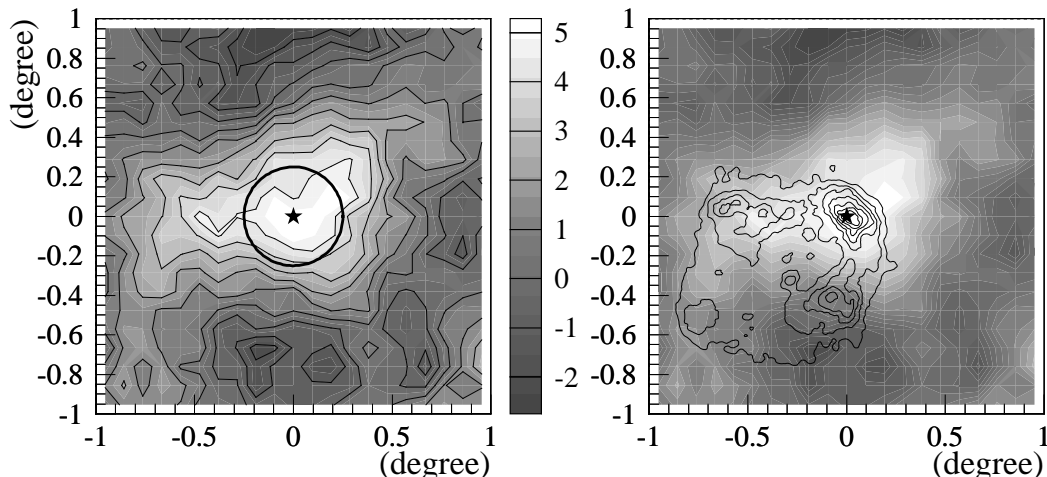


FIGURE 2. CANGAROO observations of RXJ 1713.7-3946. The left plot shows the excess in TeV γ -rays and the right plot superimposes the X-ray map of synchrotron emission over the TeV γ -ray map. Figure from [3].

TABLE 2. Extragalactic Sources of VHE γ -rays.

Source	z	Energy	Flux	Significance
Mrk 421	0.031	>0.50 TeV	0.3 Crab	Conf. ^a
Mrk 501	0.034	>0.30 TeV	0.08 Crab	Conf.
1ES 2344+514	0.044	>0.35 TeV	0.11 Crab	5.2σ
PKS 2155-304	0.116	>0.30 TeV	0.48 Crab	6.8σ
1ES 1959+650	0.048	>0.90 TeV	???	3.7σ
3C 66A	0.444	>0.90 TeV	1.2 Crab	5.0σ

^a Significances are listed only for unconfirmed sources.

EXTRAGALACTIC SOURCES

Six BL Lacertae objects (BL Lacs) have been detected as sources of VHE γ -rays: Markarian 421 (Mrk 421), Mrk 501, 1ES 2344+514, PKS 2155-304, 1ES 1959+650 [15], and 3C 66A. A summary of their properties is given in Table 2. The results quoted in the table are values from the discovery papers. Only Mrk 421 and Mrk 501 have been confirmed as VHE sources. The other objects have been detected with high significance in limited time intervals, making confirmation difficult. Mrk 421, PKS 2155-304, and 3C 66A are sources in the third EGRET catalog [6]. Mrk 501 was first detected on the ground but it has recently been claimed as an EGRET source [16].

The most distinctive feature of the VHE emission from Mrk 421 and Mrk 501 is large amplitude, rapid variability. For Mrk 421, the average flux does not change much from year to year. Instead, flares develop and decay on day-scales or less and drop to a baseline emission level (if one exists at all) that is below the sensitivity of current telescopes [17]. Fluxes from 0.1 to 10 times the Crab flux have been

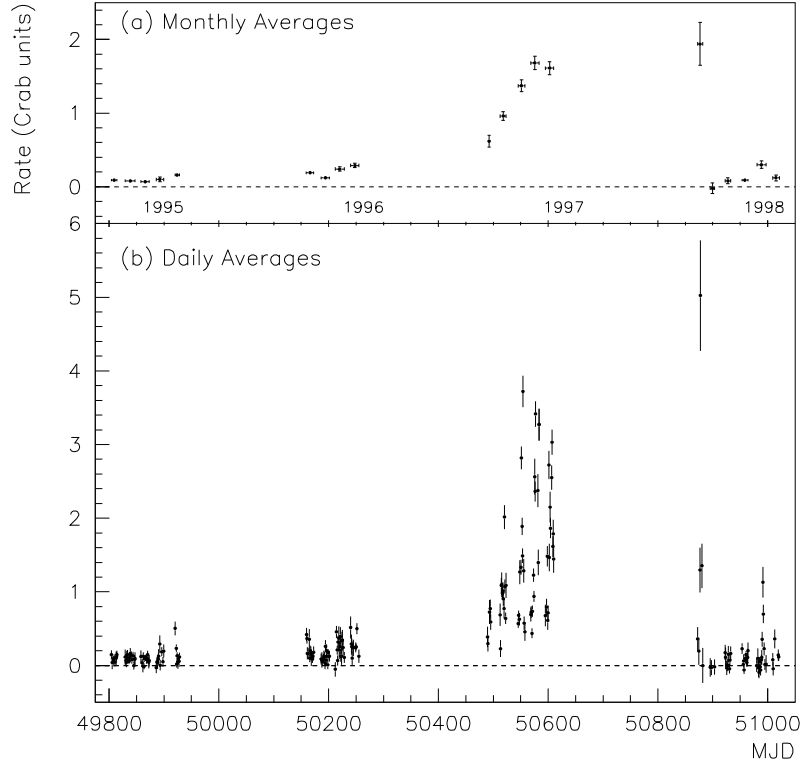


FIGURE 3. Whipple Observations of Mrk 501 between 1995 and 1998. The top plot shows monthly average fluxes and the bottom plot shows nightly average fluxes. Figure from [19].

detected and flares lasting as little as 30 minutes have been measured [18]. For Mrk 501, the flaring appears to be somewhat slower and of lower amplitude than that seen in Mrk 421 [19]. The most prominent features of the variability in Mrk 501 are large changes in its average flux and flaring activity, as shown in Figure 3. The yearly average flux has varied from 0.08 Crab in 1995 to 1.4 Crab in 1997 and the amount of day-scale flaring increases with increasing flux [19].

Perhaps the most important development in the TeV results on Mrk 421 and Mrk 501 since the 4th Compton Symposium has been accurate measurements of their spectra. Observations of several high (1 – 10 Crab) flux states between 1995 and 1996 from Mrk 421 by the Whipple collaboration show that the spectra are all consistent with a simple power law with photon index $-2.54 \pm 0.03_{\text{stat}} \pm 0.10_{\text{sys}}$ over the energy range from 0.25 – 10 TeV [20]. Observations by the HEGRA collaboration of Mrk 421 in a lower (<1 Crab) flux state in 1998 also indicate a power law spectrum, but the spectral index is $-3.09 \pm 0.07_{\text{stat}} \pm 0.10_{\text{sys}}$ over the energy range 0.5 – 7 TeV [21]. This difference could reflect a change in spectral index with flux, but neither Whipple nor HEGRA see evidence of spectral variability within their respective data sets. Further study may help resolve these differences.

Unlike Mrk 421, the spectrum of Mrk 501 during its high state in 1997 is not consistent with a simple power law. The Whipple [20] and HEGRA [22] collaborations

derive spectra of the form:

$$\begin{aligned}\frac{dN}{dE} &\propto E^{-2.22 \pm 0.04_{\text{stat}} \pm 0.05_{\text{sys}} - (0.47 \pm 0.07_{\text{stat}}) \log_{10}(E)} \quad (\text{Whipple}) \\ \frac{dN}{dE} &\propto E^{-1.92 \pm 0.03_{\text{stat}} \pm 0.20_{\text{sys}}} \times e^{-E/6.2 \pm 0.4_{\text{stat}} (+2.9_{-1.5})_{\text{sys}}} \quad (\text{HEGRA}).\end{aligned}$$

The form of the curvature term in these two expressions reflects the preferences of the authors, since the data from both groups are indistinguishable when overlaid. The average spectrum for Mrk 501 measured by the CAT group is consistent with that observed by HEGRA and Whipple [23], but the CAT data show evidence of spectral hardening during high flux states while the Whipple and HEGRA data do not. Again, further study may resolve these issues.

Mrk 421 and Mrk 501 have been the target of several intensive multi-wavelength campaigns. Observations of Mrk 421 in 1995 [17] and Mrk 501 in 1997 [24] revealed day-scale correlations between the TeV γ -ray and X-ray emissions, suggesting that both sets of photons derive from the same population of particles. The variability of the synchrotron emission increases with increasing energy, and EGRET's lack of detected variability in these studies suggests similar behavior for the high energy emission. Thus, these flares seem to be caused primarily by impulsive increases in the efficiency for acceleration of the highest energy electrons. This is not to say that the multi-wavelength behavior of Mrk 421 and Mrk 501 is identical. For example, in Mrk 421, the variability amplitude of the TeV γ -rays and X-rays is comparable while for Mrk 501, the variability amplitude is larger in the TeV γ -rays. More spectacular, is the difference in the spectral energy distributions of these two objects, as shown in Figure 4. The spectrum of Mrk 421 is typical of high-frequency peaked BL Lacs: a synchrotron peak at ~ 1 keV followed by a rapid drop-off. Mrk 501, on the other hand, appears to be an extreme version of a high-frequency peaked BL Lac, as its synchrotron spectrum peaked at 100 keV in 1997, the highest ever observed in a blazar. Also, the power output at X-ray and TeV energies in Mrk 421 is approximately equal but for Mrk 501, the TeV power can be much less than in X-rays.

Those observations do not resolve any of the hour-scale flares known to occur in Mrk 421 and Mrk 501. In 1998, a campaign involving the Whipple telescope and *BeppoSAX* had overlapping observations of an hour-scale flare from Mrk 421 as shown in Figure 5 [25]. The different energy bands exhibit a similar rise time, but the TeV γ -ray flux appears to fall-off much faster than the X-rays. Thus, at the same time that the first hour-scale correlations are seen in a TeV blazar, there is also evidence that the TeV γ -rays and X-rays in Mrk 421 may not be completely correlated on all time-scales.

CONCLUSIONS

From the previous paragraphs, it should be clear that ground-based γ -ray astronomy has become a vibrant branch of astrophysics. There are established sources

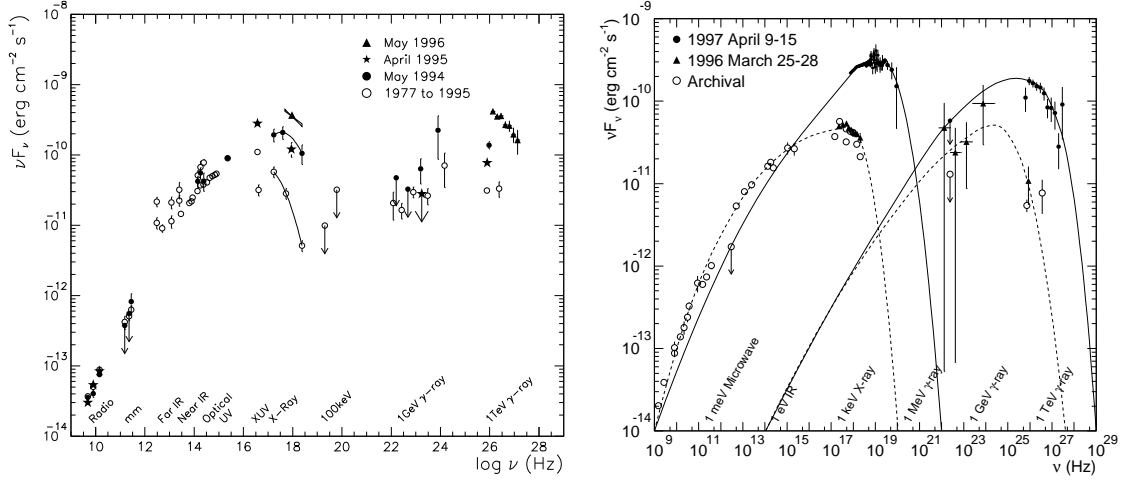


FIGURE 4. Spectral energy distributions of Mrk 421 and Mrk 501 from multi-wavelength campaigns and archival data. Figure from [1].

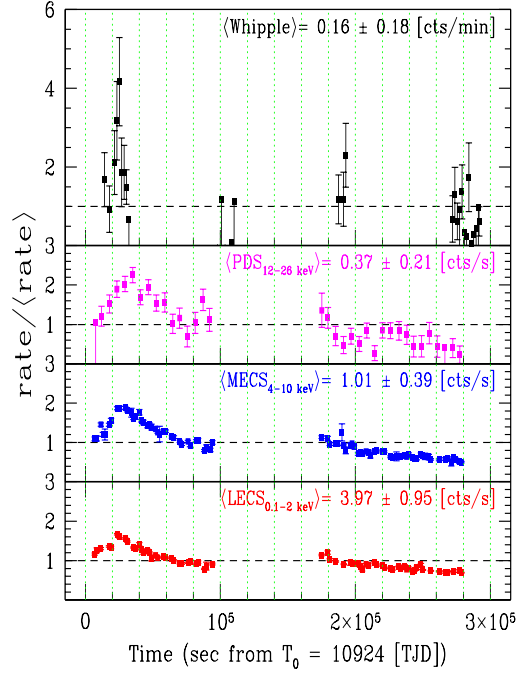


FIGURE 5. The light curve of Mrk 421 from 1998 April 21 to 24. The data are normalized to their mean during the observations (shown in each panel). The errors listed indicate the standard deviation of the data. The Whipple data are for $E > 2$ TeV. Figure from [25].

with well-measured spectra and, in the case of the BL Lacs, variability light-curves. There are several unconfirmed sources which lead me to believe that more sources are to be found in this waveband. And, there are some controversies which need resolving (e.g., do the spectra in Mrk 421 and Mrk 501 vary or not?) - which I

interpret as a healthy sign of a growing field.

However, it is also clear that many questions remain unanswered. For example, none of the sources show conclusive evidence of cosmic-ray acceleration. Also, we do not know the particle content in blazar jets, nor do we know where the emission spectra of most of the EGRET-detected blazars cut-off. Ground-based efforts, such as VERITAS [26], will dramatically improve the measurements in the VHE band. Combined with the next generation of space-based γ -ray telescopes (e.g., GLAST) and X-ray telescopes like Chandra and Astro-E, many of these questions will hopefully be answered.

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